AD-A078 370 CORNELL UNIV ITHACA N Y DEPT OF THEORETICAL AND APP--ETC F/G 11/4
ULTRASONIC NONDESTRUCTIVE TESTING OF MATERIALS.(U)
OCT 79 Y PAO , W SACHSE F49620-78-C-0100
UNCLASSIFIED AFOSR-TR-79-1174 NL

1 OF 1
AD
A078370

END
DATE
FILMED
1-80
DDC

AFOSR-TR- 79-1174

(12) LEVEL II

ADA078370

Department of
Theoretical and Applied Mechanics
CORNELL UNIVERSITY
ITHACA, NEW YORK

Approved for public release;
distribution unlimited.

79 11 27 015

(12) LEVEL II

ULTRASONIC NONDESTRUCTIVE
TESTING OF MATERIALS

Annual Report to
Air Force Office of Scientific Research

See 1473 on back

by
Yih-Hsing Pao and Wolfgang Sachse

CONTRACT No. F49620-78-C-0100

October 15, 1979

ULTRASONIC NONDESTRUCTIVE TESTING OF MATERIALS

Annual Technical Report to

Air Force Office of Scientific Research

by

Yih-Hsing Pao and Wolfgang Sachse
Department of Theoretical and Applied Mechanics
Cornell University, Ithaca, N.Y. 14853

I. INTRODUCTION

This report summarizes the progresses made during the first year of a two-year research project (August 1978 through July 1980) on the ultrasonic non-destructive testing of composite materials. The main objective of this project is to investigate theoretically and experimentally the dispersion and attenuation of ultrasonic waves in various composite materials. Specifically, researches are to be conducted in the following six ta ks:

a. Conduct ultrasonic dispersion measurements on unidirectional and cross-plied laminates of graphite-epoxy material. Investigate the microstructural characterization of these laminates based on the dispersive behavior.

b. Conduct both continuous and pulse wave ultrasonic experiments on graphite-epoxy laminates. Investigate the quantitative characterization of the dissipative behavior and the separation of the attenuation due to dispersion and dissipation.

c. Investigate the quantitative damping behavior of laminates by phase spectra techniques.

d. Develop the models necessary to make accurate predictions of the dispersion and dissipation behavior of the laminates used in the experiments to be conducted in a, b, and c above. Compare these predictions with experimental measurements.

e. Investigate the use of multiple scattering analysis to determine damping due to the presences of microstructural features in laminates.

f. Investigate the change in the experimental measurements involving dispersive and dissipative laminate properties due to mechanical loading states and/or environmental exposure conditions.

During the first year, researches were conducted on four topics:

1. Ultrasonic measurements of dispersions of waves in unidirectional and cross-plied laminates of graphite-epoxy and boron-epoxy materials.

2. Investigations of attenuation and dissipation of ultrasonic waves in composite materials.

3. Integral relations between the attenuation coefficient and the dispersion (frequency dependent phase velocity) for viscoelastic waves -- the Kramers-Kronig relation.

4. Scattering of elastic and viscoelastic waves in laminated composite with perfectly periodic layers, and with slight irregularity in layer spacings.

Details of each investigation will be given in reports, one for each topic, still in preparation. A summary of research on each topic, including some of its highlights and conclusions are presented in the next four sections.

Participating in this project during all or part of the 12 months from August 1, 1978 to July 31, 1979 were Professors Y. H. Pao (1 month, summer) and W. Sachse (2 months) and the post-doctoral associates, A. Ceranoglu and R. Weaver (both 11 months). In the Summer of 1979 three graduate students joined this project; two of them are expected to complete their M.S. degree within the next year with their thesis based, in part, on the results they are obtaining in this project.

II. DISPERSION OF ULTRASONIC WAVES IN COMPOSITE MATERIALS

Ultrasonic dispersion measurements were made in several unidirectional and cross-plied laminates of graphite-epoxy and boron-epoxy materials. From time-domain measurements it was found that the damping of 1-10 MHz broadband ultrasonic pulses propagating across the graphite-epoxy layers was typically 20 db/cm and that careful wave dispersion measurements were possible. The specimens of graphite-epoxy which were obtained typically from 0.092 to 0.316 cm in thickness. This restricted the specimen geometries for which reproducible measurements could be made. Only results obtained from measurements normal to the ply-layers will be discussed here.

The following sample materials were selected for the first series of experiments:

(i) 21 Ply Graphy-Epoxy, $0^o/90^o$ cross-plied (T300/5208).

(ii) 21 Ply Graphy-Epoxy, $0^o/90^o$ cross-plied (AS 3501-5).

(iii) 21 Ply Boron-Epoxy, $0^o/90^o$ corss-plied (4.1 mil/5505).

(iv) Unidirectional Graphite-Epoxy (GY 70/934).

(v) Carbon-Phenolic, 3-D.

(vi) Quartz-Phenolic, 3-D.

The phase and group velocities over a wide frequency range were measured by the method of phase spectroscopy. The method as well as typical results are discussed in the following.

(A) The Method of Phase Spectroscopy

The ultrasonic phase spectroscopy technique [1] had been developed, in part, under earlier AFOSR sponsorship. In this technique, the dispersion relation for a material is determined from analysis of the Fourier phase spectrum of a broadband ultrasonic pulse which has travelled a distance L in a specimen. With a Fast Fourier Transform algorithm, the propagating

pulse measured in voltage V(t) is transformed into the frequency domain $\bar{V}(f)$ where

$$\bar{V}(f) = |\bar{V}(f)|\ e^{i\phi(f)} \quad . \tag{2.1}$$

The frequency dependent wave number is then found from the phase spectrum $\phi(f)$,

$$k(f) = [\phi_o - \phi(f)]/L + 2\pi f\tau_s \tag{2.2}$$

where ϕ_o is the initial phase constant, and τ_s a time-delay constant, both can be determined experimentally. The above is also known as the dispersion relation.

The phase velocity is then given by

$$c(f) = \frac{2\pi f}{k} = \frac{2\pi fL}{[\phi_o - \phi(f)] + 2\pi f\tau_s} \tag{2.3}$$

and the group velocity is

$$v(f) = 2\pi L\left(\frac{d\phi}{df} - \tau_s\right)^{-1} \tag{2.4}$$

The differentiation of the phase spectrum can be done numerically.

This technique was applied to measure the dispersions of longitudinal waves as well as transverse waves. Typical results for dispersion of waves in graphite-epoxy and boron-epoxy are given in the following subsections.

For 3-D composites, the results obtained are similar to those in a previous report [2], and will not be discussed here.

(B) Graphite-Epoxy Composites

Fig. 2.1 shows the results of the broadband longitudinal pulse (P-wave) in a T300/5208 graphite-epoxy specimen. The signal V(t) received through a 0.30 cm thick specimen is shown in (a), and its magnitude spectrum, $|\bar{V}(f)|$, is shown in (b). The measured wave numbers k(f) which has the same shape as

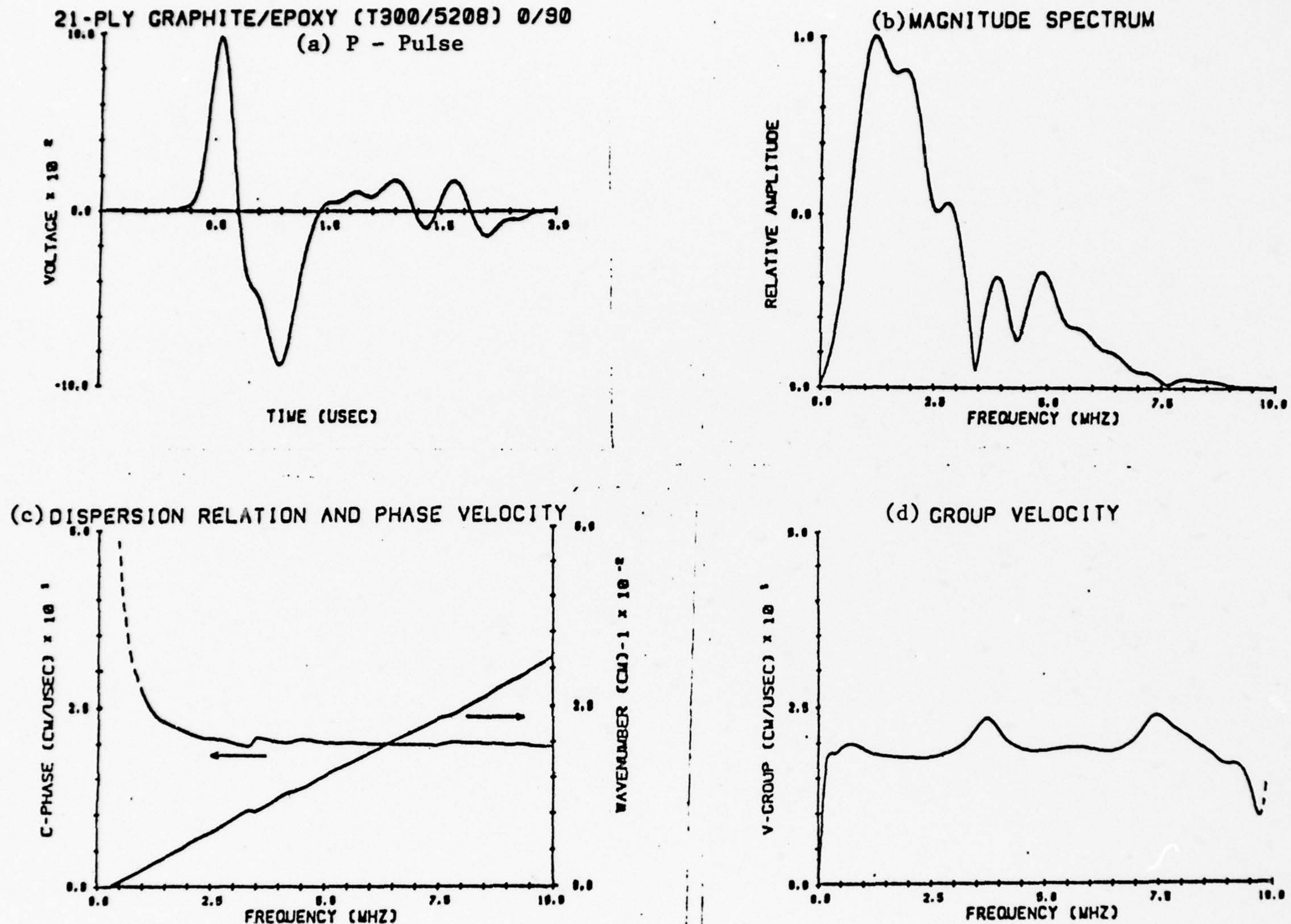

Fig. 2.1 Dispersion of a P-pulse in a graphite-epoxy specimen

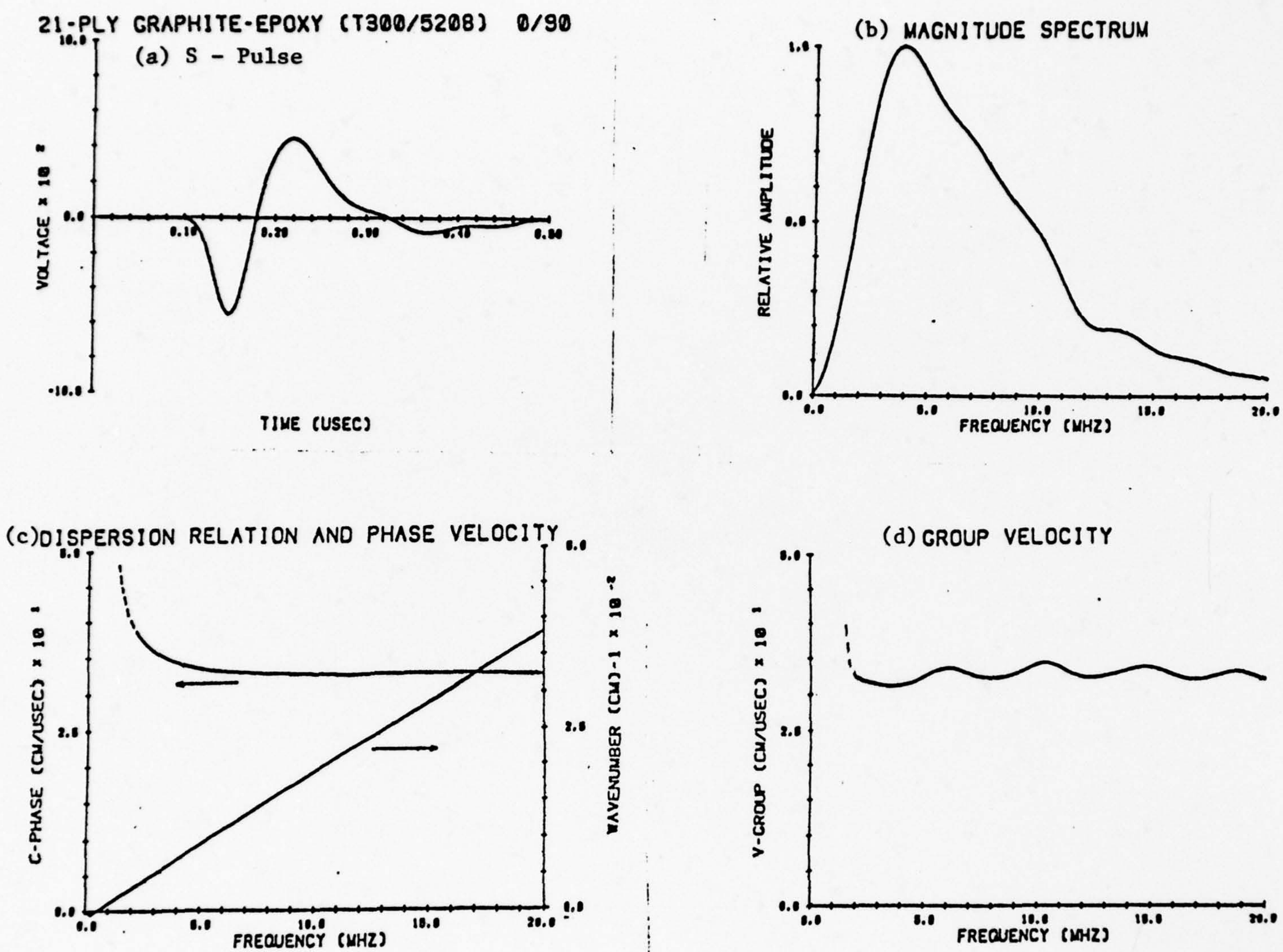

Fig. 2.2 Dispersion of a S-pulse in a graphite-epoxy specimen

the phase spectrum $\phi(f)$ as well as the phase velocity c(f) calculated from Eq. (2.3) are shown in (c); and the group velocity calculated from Eq. (2.4) is shown in (d). The corresponding results for a transverse pulse (S-wave) are shown in Fig. 2.2.

The phase velocity of longitudinal waves in Fig. 2.1c was measured to be 0.330 cm/μsec between 3 and 20 MHz, although below 3 MHz it appears to be higher. This result was observed in all the pulse spectroscopy measurements and at this time it has not been resolved whether this is an artifact of the measurement technique or whether it is a characteristic of these cross-plied laminates. This ambiguity will be resolved later either from the analysis of the propagation of elastic waves in cross-plied laminates at low frequencies, or from additional measurements on specimens of different thicknesses using the continuous wave technique [3].

The group velocity is nearly constant over the frequency range considered. Its magnitude is the same as that for the phase velocity.

As shown in Fig. 2.2, it is possible to measure shear pulse in a specimen on 21-ply graphite-epoxy up to frequencies of 10 MHz. For the range of frequencies from 2 to 10 MHz, the phase velocity of the shear waves is 0.250 cm/μsec which increases markedly at the lower frequencies. The remarks made for the low frequency regions of the longitudinal measurements may also be applicable here.

From these measurements, and others not reported here, we conclude that in the specimens of graphite-epoxy, there lacks any significant dispersion in the frequency range between 1 or 2 and 20 MHz for the longitudinal waves, and up to 10 MHz for the shear waves. These upper frequency limits appeared to be the result of transducer limitations rather than specimen size or material characteristics. This range of frequency is extended by a newly developed technique as reported in (D).

(C) Boron-Epoxy Composites

In Figs. 2.3 and 2.4, we show the results for the dispersion of waves in the composite, 4.2 mil Boron/5505. Again, Part (a) shows the received pulse, (b) the magnitude spectrum, (c) the phase spectrum and phase velocity, and (d) the group velocity.

As can be seen from the magnitude spectrum of the longitudinal pulse (Fig. 2.3), the higher frequencies of the excitation pulse are more attenuated than for pulses propagating in the graphite-epoxy specimens. In contrast to the latter, there appears to be significant dispersion in this composite. As shown in (c), the phase velocity decreases from 0.45 cm/μsec at 3 MHz to 0.32 cm/μsec at 20 MHz. Similar results are found for the frequency dependence of the group velocity in this material as shown in (d).

For shear wave propagating in this material (Fig. 2.4), the phase velocity decreases from 0.25 cm/μsec at approximately 1.5 MHz to 0.15 cm/μsec at 10 MHz. Surprisingly, however, the group velocity shown in Figure 2.4(d) decreases only marginally over this frequency interval.

The stronger dispersion is attributed to the scattering of ultrasonic waves by larger fibers in boron composite. The effect of scattering is pronounced when the microstructures of a material have dimensions of the order as, or less than, the wavelength of the ultrasonic waves propagating through the material. For materials such as boron-epoxy in which the characteristic dimensions are of the order of 0.008 cm to 0.02 cm, waves of frequencies ranging from 1 to 10 MHz will be dispersed. For materials with a finer microstructure such as the graphite-epoxy, dispersive effects due to scattering are expected to appear at higher frequencies.

(D) A New Wideband Ultrasound Generator

It was mentioned in the previous subsection that the effect of scattering,

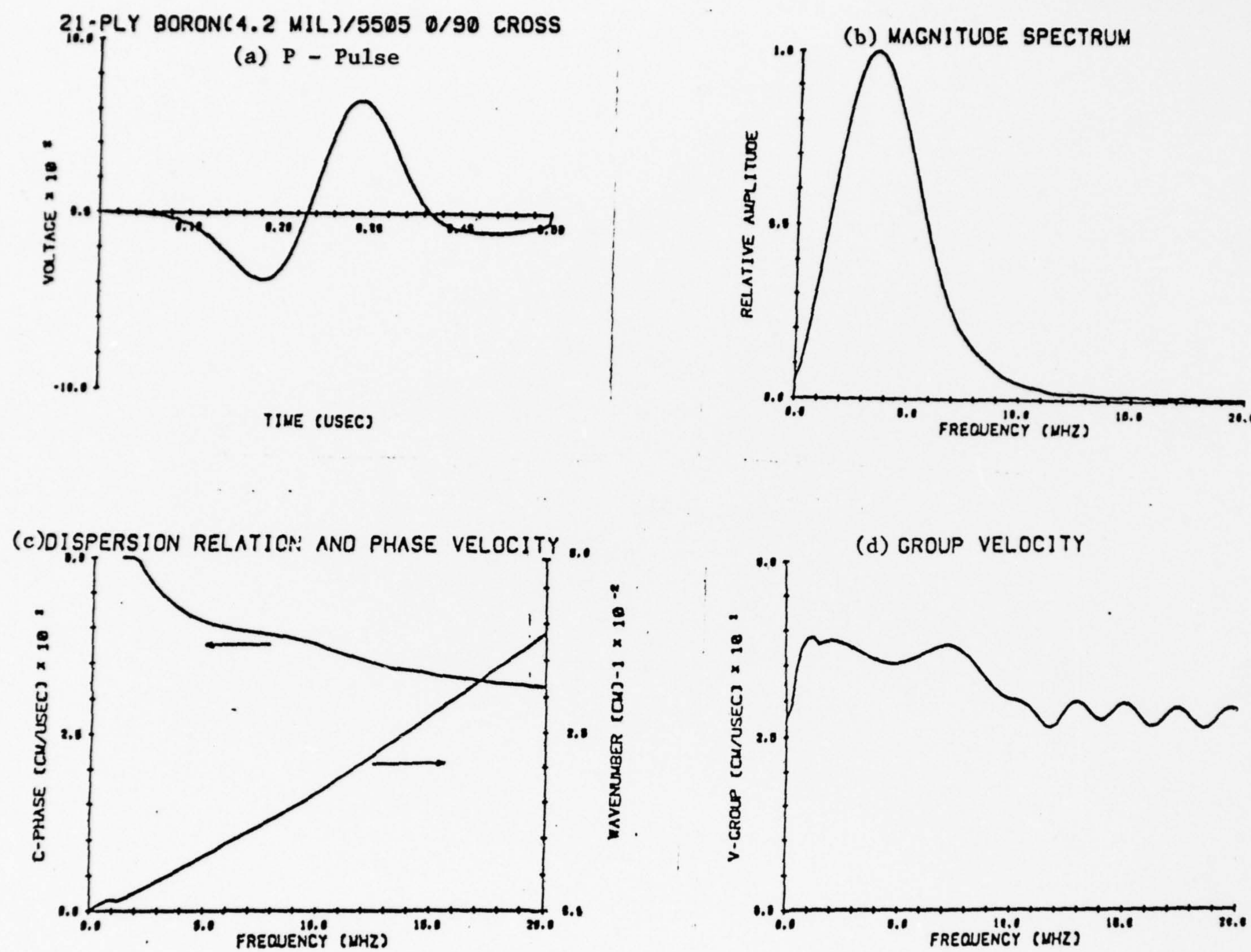

Fig. 2.3 Dispersion of a P-pulse in a boron-epoxy specimen

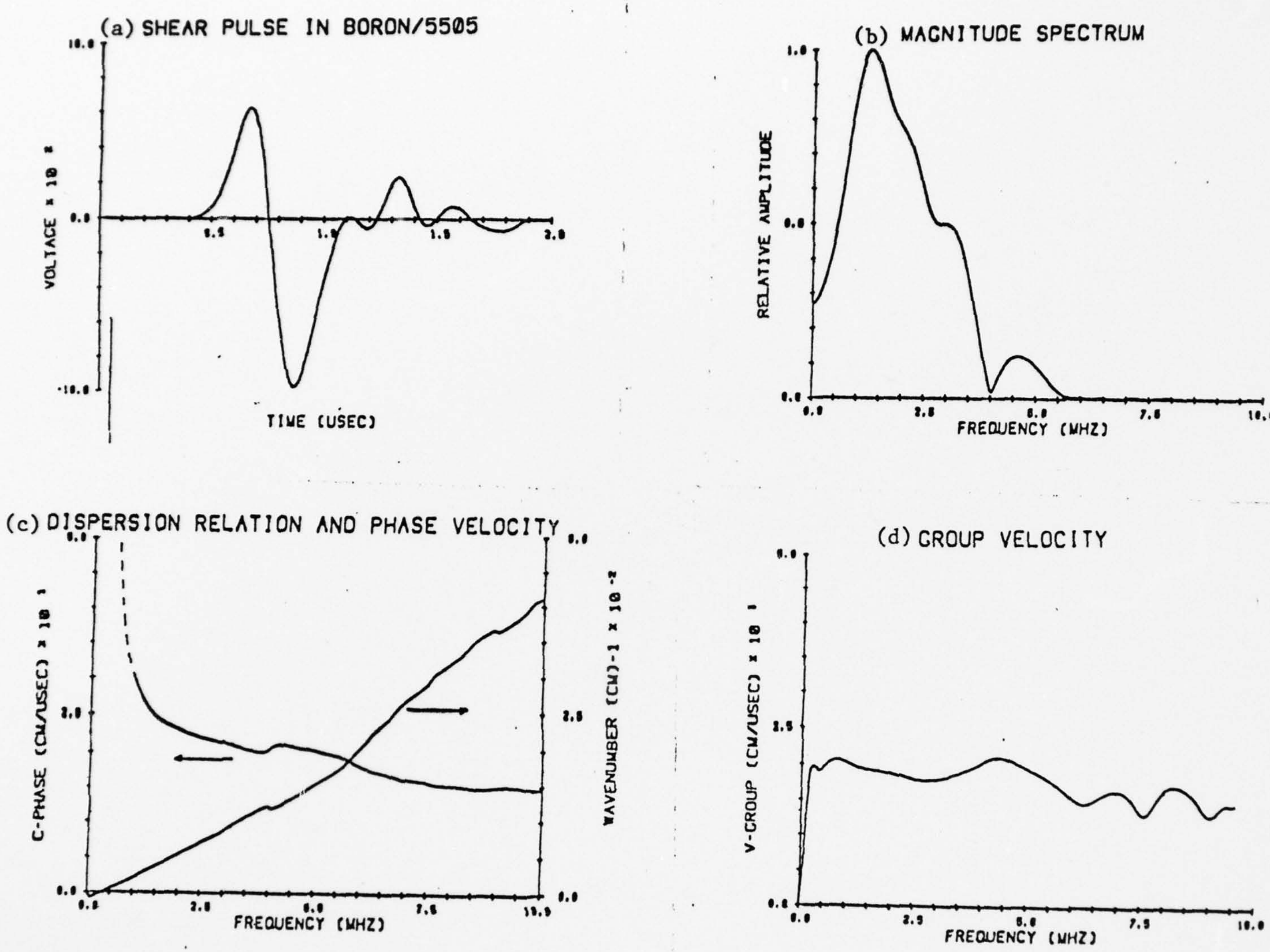

Fig. 2.4 Dispersion of a S-pulse in a boron-epoxy specimen

and hence the dispersion, is expected to be more pronounced in a composite with fine microstructures when the frequency content of the excitation is higher. However, the use of a piezoelectric transducer excited by the conventional electronic pulse generator places restrictions on the range of frequencies which can be efficiently generated as a source of ultrasound. Furthermore, much of the variability, including dispersive-like effects, arise from the couplant layer between specimen and transducer. The problem is particularly pronounced for shear wave couplants. In view of these difficulties, some thought was given to the contactless generation and detection of ultra-broadband ultrasonic waves in composite material specimens.

Electromagnetic transducers (EMATS) appear to be suitable for this particular purpose. However, their insertion loss is about 30 db higher than piezoelectric transducers, and this precludes their use, at least for now, as a broadband ultrasonic transducer for composite materials testing. Our research work has turned therefore to the development of an ultra-broadband ultrasonic source.

After many trials, we find that reproducible ultrasonic signals can be generated by an electric arc. However, there appear in the signals recorded by a piezoelectric receiver some artifacts which are directly related to the electric arc. These artifacts are eliminated when the electrical arc is used to shock-excite a high frequency broadband transducer.

Preliminary experiments with this technique utilizing a broadband longitudinal wave transducer where center frequency is 15 MHz have resulted in a clean echo pattern in a 0.3175 cm thick specimen of unidirectional graphite-epoxy (AS/3501). Shown in Fig. 2.5a are the received wide band signal (Echo 1) and the signal after one round of reflection (Echo 2). The risetime of the first echo is approximately 15 μsec and this echo contains frequency components of significant amplitude to 30 MHz (Figure 2.5b).

Measurements of the dispersion of echoes 1 and 2 made according to Eqs. (2.2) and (2.3) are shown in Figure 2.5(c), indicating that even at frequencies up to 30 MHz, dispersive effects in this graphite-epoxy specimen are still negligible.

Additional measurements with the arc technique and variations thereof will be made during the second year of this contract to further explore the potential of electrical arcs for efficiently generating ultra-broadband ultrasonic waves in composite materials.

III. ATTENUATION OF WAVES IN COMPOSITE MATERIALS

A significant portion of the research program dealt with the determination of the frequency-dependent attenuation of sound waves propagating in various composite materials. As will be reviewed later, particular attention has focused on extension of the ultrasonic phase spectroscopy technique for measuring of the attenuation associated with waves propagation in a dispersive medium (Section IV), and on the calculation of scattering losses of waves, or the attenuation of the "averaged wave", propagating through composite materials (Section V). In this section, we summarize the experimental program which makes use of the existing techniques to measure the attenuation of ultrasonic waves in materials.

(A) Techniques for Measuring Attenuation Coefficients

Many techniques have been developed for the measuring of the attenuation and dissipation of ultrasonic waves [4], [5]. Some of them have been tried by us for graphite-epoxy materials with mixed results, which are summarized in the following.

(1) Resonance Technique. In this technique, continuous waves with slowly changing frequency are generated at one side of a specimen. While the reflected signals can be detected by the same transducer, most generally a second trans-

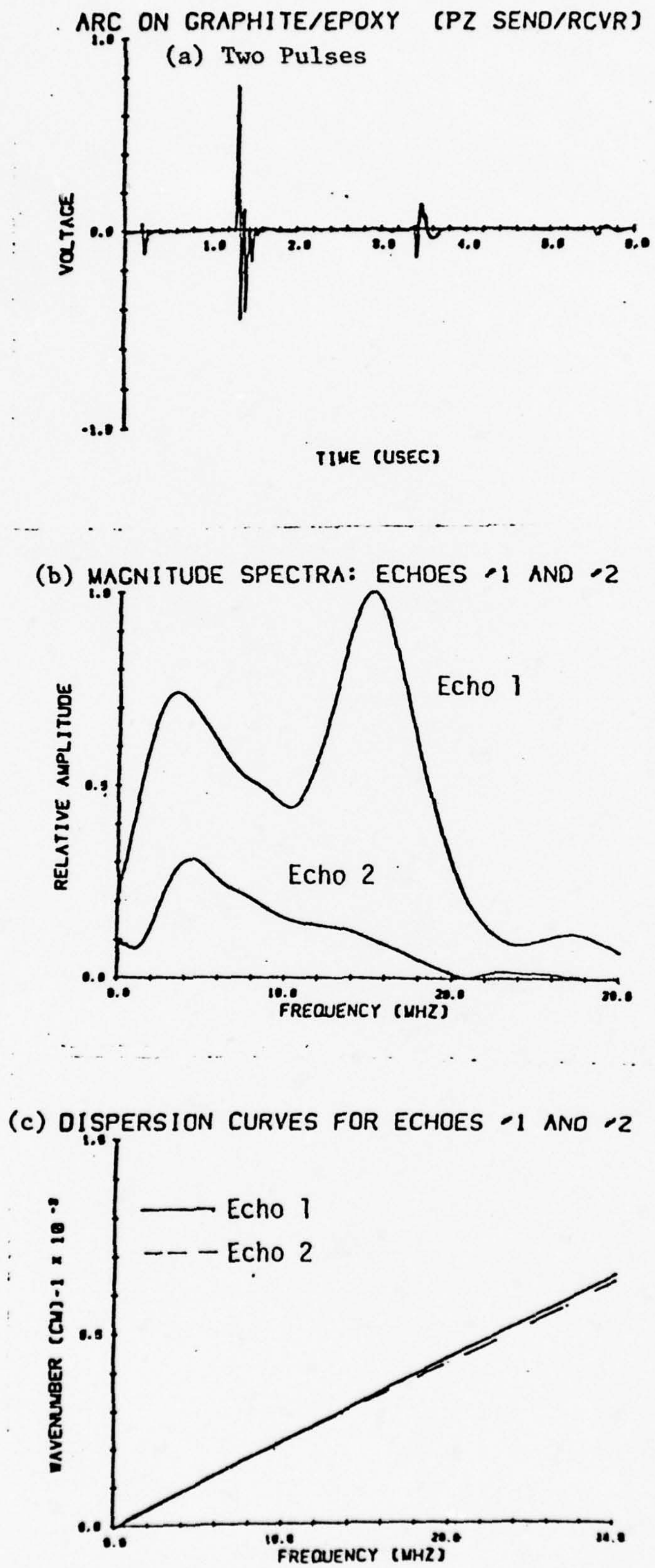

Fig. 2.5 Dispersion of an ultra-wideband signal generated by a piezoelectric transducer excited by an electric arc

ducer on the opposite side is used as the detector. The resonant frequencies of the specimen are recorded and the damping (Q or logarithmic decrement) can thus be determined directly from the half-power points of the resonance curve.

For composite materials, however, we found that the damping is so high that the resonance curve does not pass through the half-power points, precluding their determination. For this reason, such measurements have not been pursued further this year.

(2) R.F. Burst Method. In this technique, radio frequency (r.f.) bursts of various center frequencies are sent into a specimen. Using either the same transducer or another,one can determine the logarithmic decay of successive echoes bounced back and forth in the specimen [4, Sect. 15].

However, this method is not applicable to materials with high losses when only one or two echos are discernable. We have tried this method for graphite-epoxy materials without much success, especially at high frequencies.

(3) Broadband Pulse Echo Method. A modification of the previous method is to transmit a broadband pulse and to record the echos. If $V_1(t)$ is the voltage output of the first echo, and $V_2(t)$ that of the second echo after the pulse being reflected twice in the specimen, the attenuation coefficient is given by

$$\alpha(f) = \frac{20}{L} \log_{10} \frac{\overline{V}_2(f)}{\overline{V}_1(f)} \text{ (db/length)} \tag{3.1}$$

where $\overline{V}_j(f)$ are the Fourier transforms of $V_j(t)$, and L is the round trip distance travelled by the reflected pulse.

This technique depends on the presence of at least two echoes. The high damping of ultrasonic waves in composite materials often precludes the presence of a second echo and so renders this technique ineffective. A variation of this which has been used in our work is to place two transducers (source and receiver) in intimate contact, measuring the received voltage $V_o(t)$.

This can be transformed into the frequency domain to give $\overline{V}_o(f)$. The specimen is then inserted between the transducer and the receiver and another signal is measured, giving V(t) and $\overline{V}(f)$. Then the frequency-dependent attenuation is determined by

$$\alpha(f) = \frac{20}{L} \log_{10} \frac{|\overline{V}(f)|}{|\overline{V}_o(f)|} \text{ (db/length)} \qquad (3.2)$$

The use of this technique is illustrated in the subsection (B).

(4) Other Techniques. Various other techniques for measuring the frequency-dependent attenuation of ultrasonic waves in composite materials have been considered. One which appeared promising was the pulse reflection technique in which a broadband ultrasonic pulse is reflected from an interface between a non-dispersive buffer rod and the composite specimen. This permits determination of the frequency-dependent interface reflection coefficient, R(f), and specimen attenuation, $\alpha(f)$. It has, however, been found that these measurements appear to be very sensitive to the nature of the buffer-specimen interface which can lead to significant errors in the frequency-dependent attentuation determination.

(B) Attenuations in Graphite-Epoxy Composites

The modified broadband pulse-echo technique was applied to determine the attenuation coefficient $\alpha(f)$ for a 21-ply graphite-epoxy specimen (AS 3501-5), and for a 96-ply unidirectional boron-epoxy. The results for the graphite-epoxy are shown in Fig. 3.1(a)-(d).

Fig. 3.1(a) shows the broadband longitudinal pulses $V_o(t)$ when the transmitter and receiver are in contact (excitation voltage), and the signal voltage V(t) after the insertion of the specimen in between the transmitter and receiver (Echo 1). The length of the specimen is 0.30 cm. The received signal appears very weak when it is displayed on the same scale with the

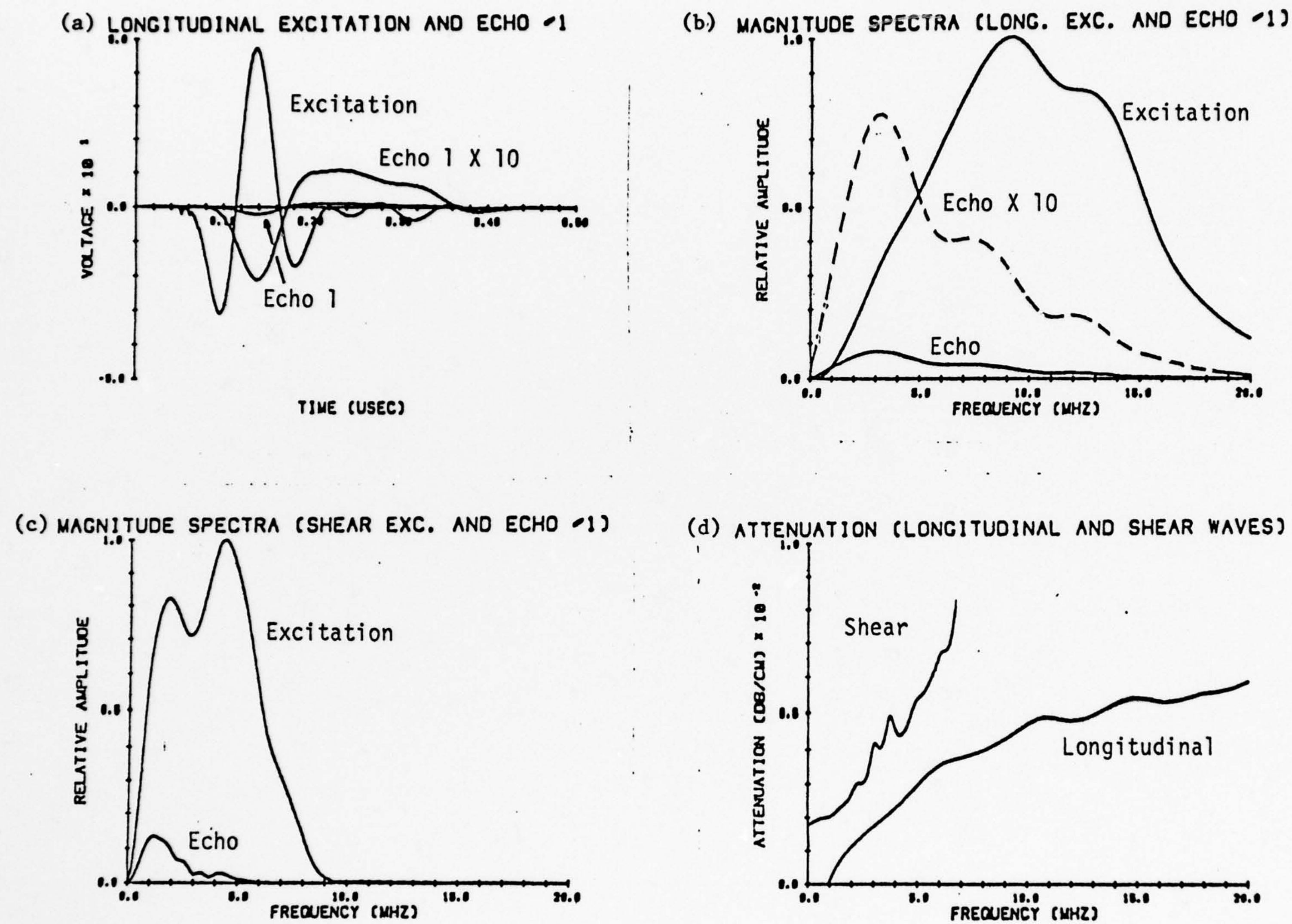

Fig. 3.1 Attenuations of P- and S-Pulses in a Graphite-Epoxy Specimen

excitation voltage. Therefore a 10 times amplification of the same signal is also shown in Fig. 3.1(a).

The Fourier transforms of these two signals, $\overline{V}_o(f)$ and $\overline{V}(f)$, are shown in Fig. 3.1(b) and the attenuation coefficient $\alpha(f)$ calculated according to Eq. (3.2) is shown in Fig. 3.1(d) marked "longitudinal". Although we cannot ascertain the accuracy of measurements at this stage, the calculated $\alpha(f)$ is of the right order of magnitude and the correct trend of increasing with the frequencies.

Experiments with shear pulses in the same specimen are also conducted, and the results are shown in Figs. 3.1(c) and (d). The record of the shear pulses is omitted. It is seen from (d) that the attenuation coefficient $\alpha(f)$ for shear waves is larger than that for the longitudinal waves.

IV. KRAMERS-KRONIG RELATIONS FOR DISPERSION OF ULTRASOUND

For electromagnetic wave propagation in homogeneous dielectrics, there exist the Kramers-Kronig relations [6] which state that the attenuation coefficient of the wave is related to the phase velocity by an integral involving the latter over all frequencies ω, and vice versa. It was thought that similar relations might apply for acoustic and stress waves in homogeneous media, and perhaps also for the average wave in random media. If applicable, these relations will enable us to determine the attenuation coefficient $\alpha(\omega)$ from the dispersive phase velocity $c(\omega)$, and vice versa, essentially by finding one from the Hilbert transform of the other.

Recently, O'Donnell et al. [7] applied the Kramers-Kronig relations to the investigation of attenuation of sound waves in biological materials. Since the damping is small, they developed approximate formulas for calculating $c(\omega)$ and $\alpha(\omega)$ directly from the complex bulk modulus of the material. For higher values of damping, as encountered in composite materials, the full integral relations

must be used.

(A) Kramers-Kronig Relations

An attenuated plane wave propagating in the direction of x can be expressed by

$$e^{i(kx-\omega t)} = e^{-\alpha x} e^{-i\omega(t-x/c)} \tag{4.1}$$

where both the attenuation coefficient $\alpha(\omega)$ and phase velocity $c(\omega)$ are functions of the real frequency ω. The complex wave number, $k(\omega)$, is given by

$$k(\omega) = k_1(\omega) + ik_2(\omega) = \frac{\omega}{c(\omega)} + i\alpha(\omega). \tag{4.2}$$

According to Ginsburg [8], the $c(\omega)$ and $\alpha(\omega)$ are related by

$$\frac{1}{c(\omega)} - \frac{1}{c_\infty} = -\frac{1}{\pi} \int_{-\infty}^{\infty} \frac{\alpha(\xi)/\xi - (\alpha/\omega)_\infty}{\xi - \omega} d\xi \tag{4.3}$$

$$\frac{\alpha(\omega)}{\omega} - (\frac{\alpha}{\omega})_\infty = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{1/c(\xi) - 1/c_\infty}{\xi - \omega} d\xi \tag{4.4}$$

In the above equations, c_∞ is the value for $c(\omega)$ as $\omega \to \infty$, and $(\alpha/\omega)_\infty$ that for $\alpha(\omega)/\omega$ as $\omega \to \infty$. Only principle values of the integrals are taken. The pair of integrals define the Hilbert transforms of the quantities $c^{-1} - c_\infty^{-1}$ and $\alpha/\omega - (\alpha/\omega)_\infty$.

It was shown in Eq. (2.3) that for a dispersive medium, the $c(\omega)$ can be measured from the phase spectrum ($\omega=2\pi f$). Knowing c_∞ from the theory or from other sources, we can then calculate $\alpha(\omega)$ from Eq. (4.4). For convenience of numerical work, Eq. (4.4) is reduced to the following form,

$$\alpha(\omega) = A\omega + \frac{2}{\pi}\omega^2 \int_0^{\infty} [\frac{1}{c(\xi)} - \frac{1}{c_\infty}] \frac{d\xi}{\xi^2-\omega^2} \tag{4.5}$$

where $A = (\alpha/\omega)_\infty$ is a constant. A computer code has been developed to evaluate this integral for given constants A and c_∞, and the phase velocity function $c(\omega)$.

(B) Application to Viscoelastic Solids

The formula (4.5) was tested for the Voigt viscoelastic solid, for which the stress-strain relation is

$$\tau = G\varepsilon + \eta\dot{\varepsilon} , \qquad \varepsilon = \partial w/\partial x \tag{4.6}$$

where G is the shear modulus, η the viscosity, and w is the transverse displacement perpendicular to the x-axis. The equation of motion is

$$G \frac{\partial^2 w}{\partial x^2} + \eta \frac{\partial^3 w}{\partial t \partial x^2} = \rho \frac{\partial^2 w}{\partial t^2} \tag{4.7}$$

where ρ is the mass density.

For a wave of the form given by Eq. (4.1), both k_1 and k_2, or $c(\omega)$ and $\alpha(\omega)$ can be precisely calculated from these equations as a function of ω. The curve for $\alpha(f)$ while $f = \omega/2\pi$ in MHz is shown in Fig. 4.1, marked "exact".

Substituting the known function $c(\omega)$ into Eq. (4.5) and then calculating $\alpha(\omega)$ numerically, the resulting $\alpha(f)$ is also shown in Fig. 4.1 with a label "K-K relation". These two curves are almost coinciding for the entire frequency range shown.

This method is being tested on experimental data for shear waves in homogeneous epoxy material. Results will be reported in a forthcoming paper. Since the Kramers-Kronig relations are a consequence of causality and homogeneity [9] and as composites are not homogeneous, whether such relations exist for fiber reinforced composite materials remains to be tested.

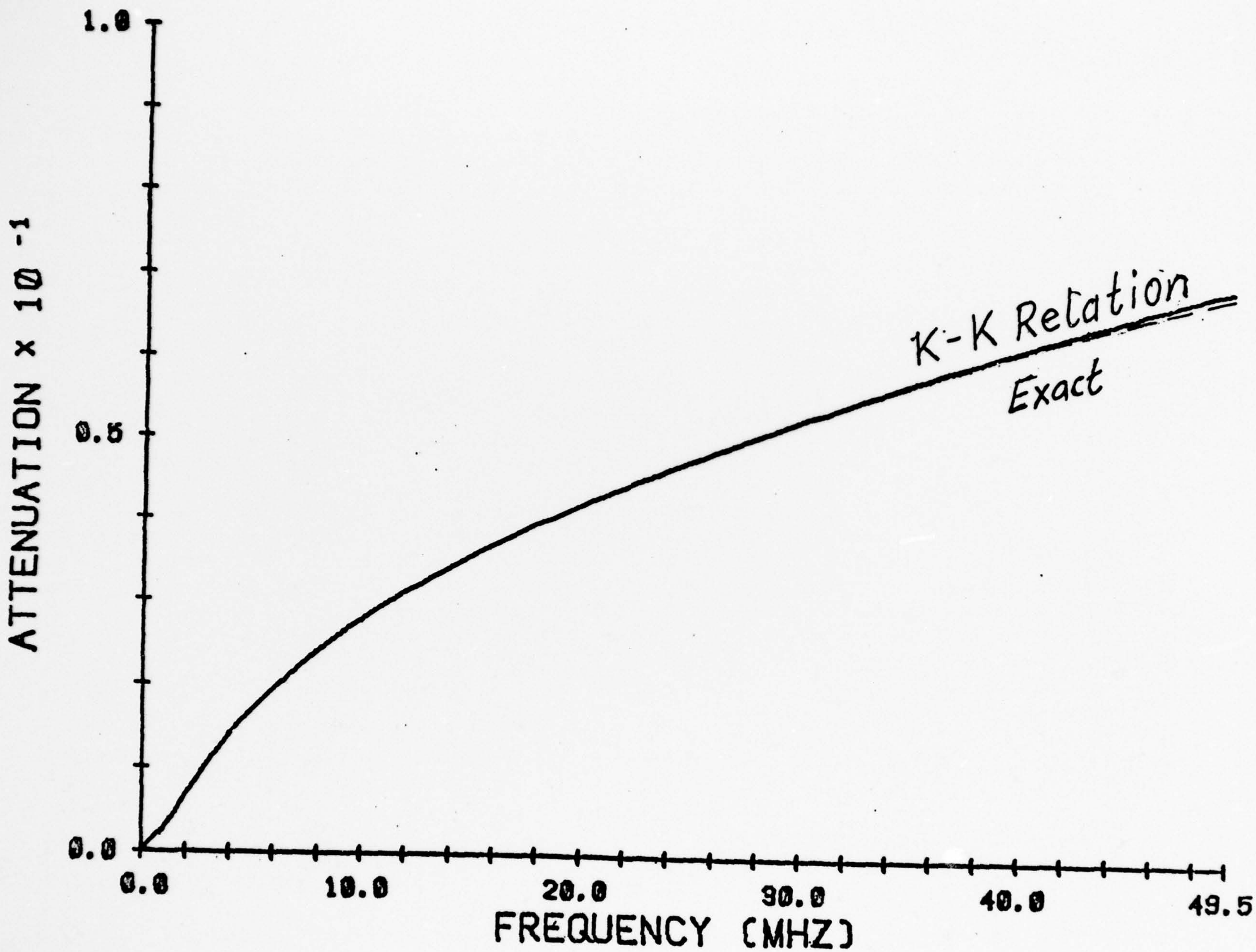

Fig. 4.1 Attenuation of Harmonic Waves in a Voigt Solid

V. SCATTERING AND ATTENUATION OF WAVES IN PERIODIC LAYERS OF VISCOELASTIC MATERIALS

The dispersion and attenuation of stress waves propagating through a composite medium is attributed to the scattering losses by the elastic fibers and viscosity in the matrix material, assuming that the fibers are perfectly bounded to the matrix material. If the attenuation for waves in such a medium can precisely be determined, then any measurable addition to the attenuation is attributed to the development of defects such as delamination, voids, and fiber breakage in the medium. This is the main motivation in undertaking this research project.

Scattering losses can further be divided into two parts. One is due to the exactly periodic arrangement of the fibers, or layers of parallel fibers, which is analogous to the band gap, or stop-band loss for waves through perfect crystal lattices [6]. Another is the loss due to the slight irregularity in the periodic spacing of fibers, or layers. This has no counterpart in crystal lattice and hence is less understood. We shall refer to the former as the "stop-band loss", and the latter as the "irregularity loss". By loss here we do not necessarily mean that energy is dissipated into heat or other form of energy. In the case of stop-band loss, the incident wave cannot penetrate the material, and is blocked from transmitting through the medium.

In order to gain insight into the three main causes of dispersion and attenuation in composites, the stop-band, the irregular periodicity, and the viscosity, and to separate their effects, we construct a simple model wherein certain assumptions could be tested and different approaches to wave propagation in the model medium be compared. The model is composed of large numbers of periodically spaced parallel layers, and it simulates a laminated composite material. The layers are alternately made of two different elastic

materials, or one elastic and one viscoelastic. The spacing between the layers can be either perfectly equal, or periodic with slight irregularity (Fig. 5.1). This model has the added advantage that samples for experimental testing are readily produceable.

Wave propagation in regularly spaced layered media is most often treated by a continuum theory [10], which has not been applied (and may not be applicable) to laminar composites with arbitrary correlations. One does not usually think of a wave as being scattered by a layer, but rather being reflected or transmitted. Nevertheless the concept of scattering in one dimension is adopted and the statistical theory of multiple scattering together with the method of transition matrix [11] is applied to this one dimensional problem.

The complete theory, analysis, and results of dispersion and attenuation of waves in such a laminated medium are contained in a forthcoming report. It is entitled "Multiple Scattering of Waves in Irregularly Laminated Composites" (by R. Weaver and Y. H. Pao) and is near completion. We omit the theory and analysis here, and show some of the final results.

In the model, the layers which represent laminas of parallel aligned fibers are made of elastic material with density ρ_f and shear modulus G_f, and have constant thickness 2h. The spacing between the periodic elastic layers is constant d for perfectly periodic structure, or d plus or minus a 20 percent variation for the structure with slight irregularity. The filling matrix has material constants ρ_o and G_o if it is elastic, and has an additional relaxation time, $t_o = \eta_o/G_o$, if it is Voigt viscoelastic (cf. Eq. 4.6). In the figures shown here, we have assumed $G_f = 8G_o$, $\rho_f = 2\rho_o$, $d = 5h$, and $t_o = d/(10c_o)$ where $c_o^2 = G_o/\rho_o$.

Fig. 5.2 shows the attenuation as a function of the real frequency $\omega d/c_o$ for two elastic laminates: (A) Exactly periodic elastic layers,

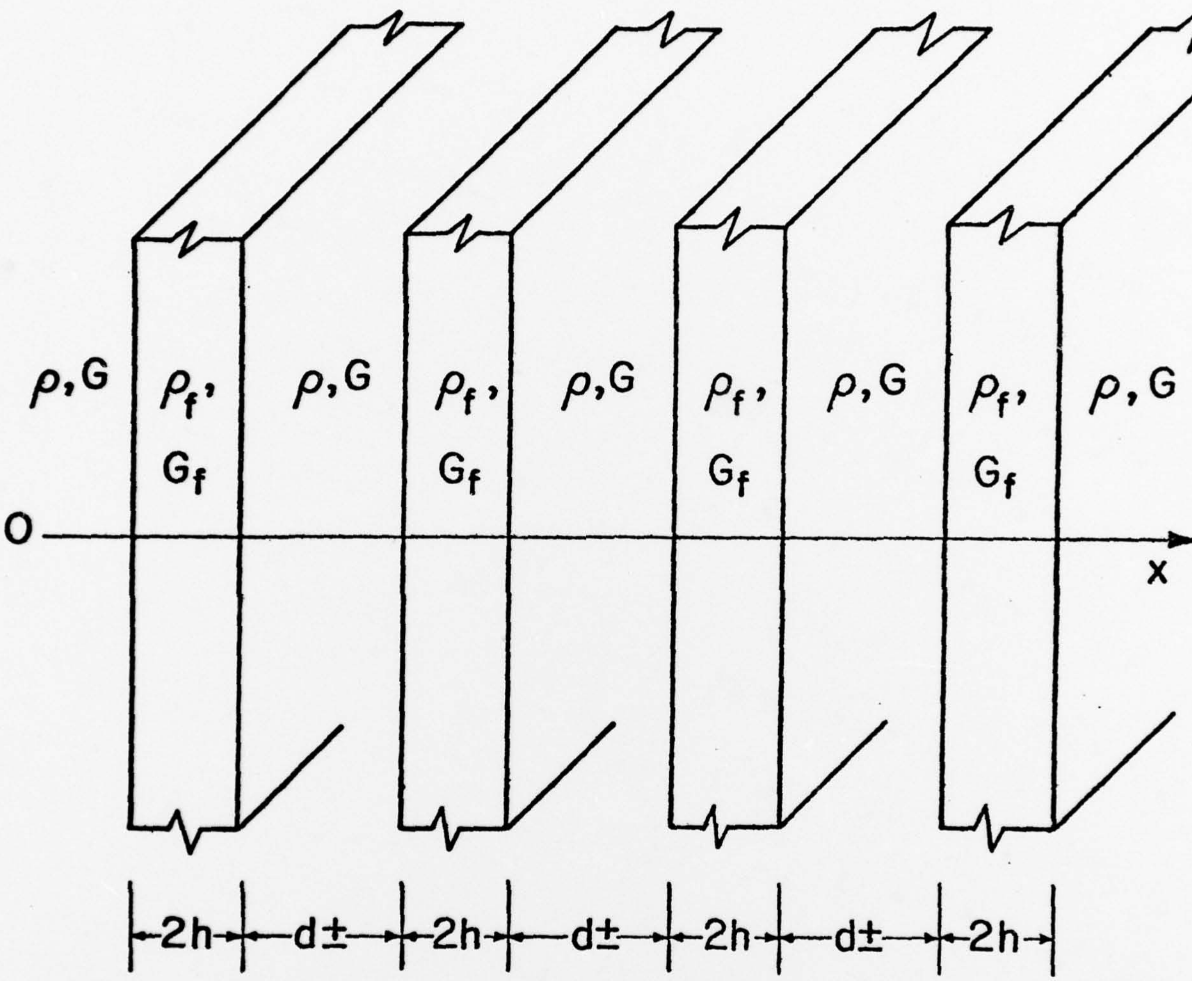

Fig. 5.1 Geometry of a Laminated Composite

(B) Elastic layers with 20 percent variation in the spacing d. The curve (A) represents the "stop-band loss", and curve (B) the stop-band loss plus scattering loss due to irregular spacing of layers. Both curves are obtained from the dispersion equation for the average wave based on the statistical theory of multiple scattering. The curve (A) however agrees completely with the result based on the exact theory [10, appendix].

Fig. 5.3 shows the additional effect of viscosity in the matrix layers. Curve (C) is for the exactly periodic layers, one family being elastic, the other being viscoelastic. Curve (D) is for the same materials but the layer spacing is 20 percent irregular. For purpose of comparison, we show also, as curve (E), the attenuation of waves in a homogeneous Voigt viscoelastic solid. For elastic materials as in cases (A) and (B), the viscosity loss is obviously zero.

By comparing curve (A) with (C), and (B) with (D), we find that outside the stop-band ($\omega d/c_o \ll 2.55$) the attenuation is primarily due to the viscosity of the matrix material. Near the stop-band ($\omega d/c_o \sim 2.55$), the scattering loss due to irregular spacing is important. For $2.55 < \omega d/c_o < 4.80$, the stop-band loss is predominant.

In all cases of layered medium, the stop-band loss is an obvious feature. In frequencies below the stop-band it is clear that attenuation due to viscosity and the attenuation due to scattering by irregularities are roughly additive. Within the band gap where apparent attenuation is primarily caused by the periodicity which coherently conspires to expel the wave from the medium, the attenuation was approximately equal in all 4 cases, though it appears that irregularity but not viscosity seems to lessen the attenuation in the gap. The effect of the irregularity has been to soften the sharp band features of the fully periodic case, spreading and diluting the strong attenuation over a wider frequency interval. Incidentally, the results in

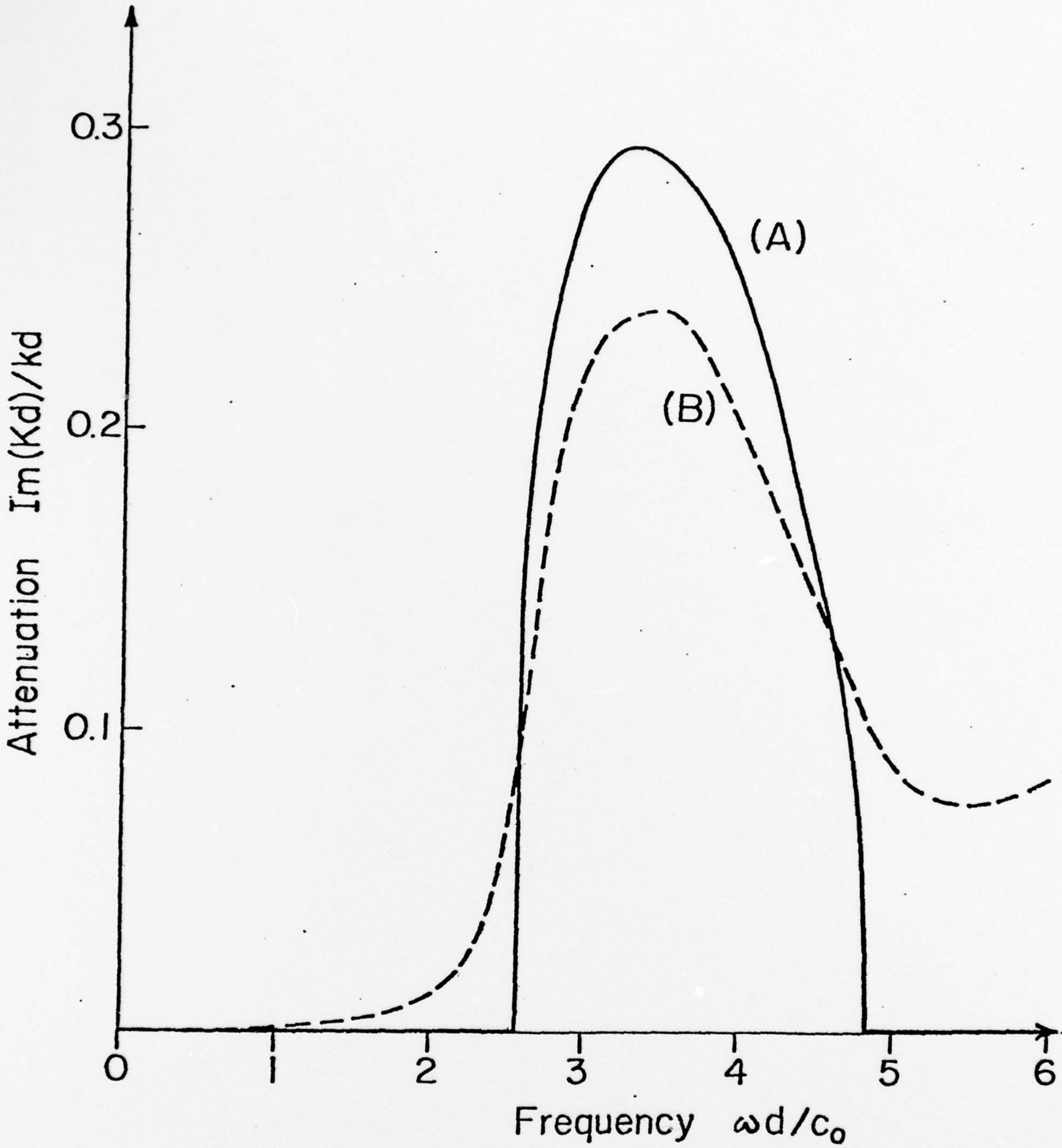

Fig. 5.2 Attenuation of an Elastic Laminated Composite

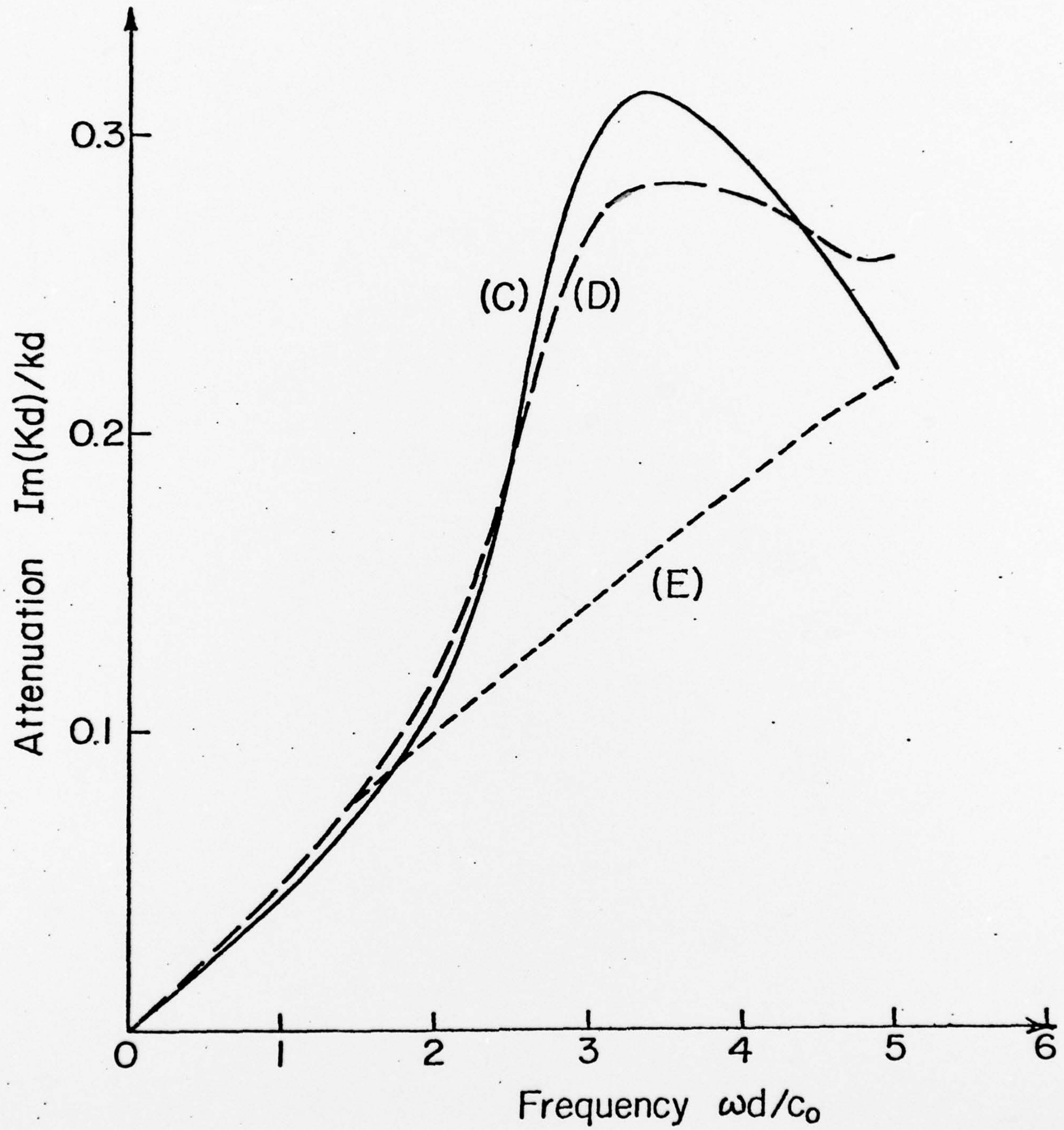

Fig. 5.3 Attenuation of an Elastic-Viscoelastic Laminated Composite

case (C) as obtained from the statistical theory of multiple scattering are in full agreement with the predictions of an exact theory with complex moduli.

VI. CONCLUSIONS

In context of the six tasks to be completed under the terms of this research program, the following is a summary of the results obtained during the first year.

Ultrasonic dispersion measurements have been made in a unidirectional as well as several cross-plied laminates of graphite-epoxy. The wave propagation in the frequency range from 1 to 20 MHz is typically non-dispersive. In a composite material which exhibits dispersion (such as in certain directions of a unidirectional boron-epoxy) very slight changes in the dispersion become apparent with thermal treatments, but the connection to specific microstructural changes still needs to be made.

Various techniques for measuring the frequency-dependence of ultrasonic attenuation of longitudinal and shear waves have been implemented. Attenuation measurements have been completed in several graphite-epoxy and boron-epoxy composite specimens.

The theory of ultrasonic phase spectroscopy has been extended to permit determination of the dispersion-related attenuation of ultrasonic waves in composite materials. A computer algorithm for performing such determinations was implemented and it has been tested with waveforms expected for a model viscoelastic material (Voigt solid).

Finally, a successful attempt has been made to delineate the scattering loss and viscosity loss in a composite material. This is made possible by applying a statistical theory of multiple scattering to a layered structure of elastic and viscoelastic materials, which models a laminated composite.

REFERENCES

[1] W. Sachse and Y.H. Pao, "On the Determination of Phase and Group Velocities of Dispersive Waves in Solids", J. Appl. Phys. 49, 4320-4327, 1978.

[2] W. Sachse, C.S. Ting and A.L.P. Hemenway, "Dispersion of Elastic Waves and the Nondestructive Testing of Composite Materials", Composite Materials: Testing and Design, ASTM STP 674, S.W. Tsai, Ed., American Society for Testing and Materials, 1979, pp. 167-183.

[3] C.S. Ting and W. Sachse, "Measurement of Ultrasonic Dispersion by Phase Comparison of Continuous Harmonic Waves", J. Acoust. Soc. Am. 64, 852-857, 1978.

[4] R. Truell, C. Elbaum, and B.B. Chick, Ultrasonic Methods in Solid State Physics, ch. 2, Academic Press, New York, 1969.

[5] E. P. Papadakis, "Ultrasonic Velocity and Attenuation: Measurement Methods with Scientific and Industrial Applications", Physical Acoustics, v. 12, ed. W.P. Mason and R.N. Thurston, Academic Press, New York, 1976.

[6] F.C. Brown, The Physics of Solids, Section 8.6, W.A. Benjamin Inc., New York, 1967.

[7] M. O'Donnel, E.T. Jaynes, and J.G. Miller, "General Relationships between Ultrasonic Attenuation and Dispersion", J. Acoust. Soc. Am. 63, 1935-1936, 1978.

[8] V.L. Ginsburg, "Concerning the General Relationship between Absorption and Dispersion of Sound Waves", Soviet Physics - Acoustics, 1,32-43, 1955.

[9] H.M. Nussenzveig, Causality and Dispersion Relations, Academic Press, New York, 1972.

[10] C.T. Sun, J.D. Achenbach and G. Herrmann, "Continuum Theory for a Laminated Medium", J. Appl. Mechanics, 35 (Trans. ASME 90), 467-475, 1968.

[11] V.K. Varadan, V.V. Varadan, and Y.H. Pao, "Multiple Scattering of Elastic Waves by Cylinders of Arbitrary Cross Section, I, SH Waves", J. Acoust. Soc. Am., 63, 1310-1319, 1978.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

18

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFOSR-TR- 79-1174
2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): 6 ULTRASONIC NONDESTRUCTIVE TESTING OF MATERIALS
5. TYPE OF REPORT & PERIOD COVERED: INTERIM 1 Aug 78 - 31 Jul 79
6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): 10 YIH-HSING PAO, WOLFGANG SACHSE
8. CONTRACT OR GRANT NUMBER(s): 15 F49620-78-C-0100
9. PERFORMING ORGANIZATION NAME AND ADDRESS: CORNELL UNIVERSITY, THEORETICAL AND APPLIED MECHANICS DEPARTMENT, ITHACA, N Y 14853
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 2307B2, 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS: AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA, BLDG 410, BOLLING AIR FORCE BASE, D C 20332
12. REPORT DATE: 11 15 ~~October~~ Oct 1979
13. NUMBER OF PAGES: 29
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): 16 2307, 17 B2
15. SECURITY CLASS. (of this report): UNCLASSIFIED 12 31
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

19 TR-79-1174

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

9 Annual rept. 1 Aug 78 - 31 Jul 79,

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

NONDESTRUCTIVE TESTING
COMPOSITE MATERIALS

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The method of phase spectroscopy was applied to measure dispersions of longitudinal and transverse waves in graphite-epoxy and boron-epoxy composite materials over a wide frequency range. A method to determine the attenuation from the dispersion based on the Kramers-Kronig relations was developed. To separate the attenuation due to scattering, and that due to viscosity, dispersion and attenuation of waves in a laminated viscoelastic composite material was analyzed using a statistical theory of multiple scattering.

404 620 JOB

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED